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# WATER-MODERATED REACTOR CONCEPT

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## INTRODUCTION

Because of the importance of nuclear rockets for manned planetary flight, the Lewis Research Center has been studying alternate nuclear rocket concepts that have the potential for meeting the high performance requirements of these missions. Lewis has concentrated its advanced nuclear rocket research program on a tungsten-water-moderated concept. The purpose of this presentation is to describe this concept and give a brief résumé of some of the work that has been done in support of it.

## NUCLEAR ROCKET REQUIREMENTS

Before getting into the details of the tungsten-water-moderated concept, some of the requirements of a nuclear rocket should be considered that lead to its choice. They are: (1) high temperature to produce the highest possible specific impulse; (2) recyclability, the ability to start up and shut down of the order of 100 times; (3) long life, that is, operating life of about 10 hours; and (4) developability, that is, the capability of being developed into a reliable man-rated powerplant with the least expenditure of cost and time.

The requirement of high temperature is, of course, obviously important to high-energy space missions such as 1-year manned trips to the nearby planets. Recyclability is of importance, not so much for missions that require restarts, but for a development program where thousands of tests are required to develop the required reliability for man-rated systems. Recyclable nuclear rocket reactors are essential to prove reliability of the entire nuclear powerplant within a reasonable amount of time.

Long operating life (compared with chemical rocket life) is required to provide the large total impulses required for lunar ferry and high-energy manned planetary missions. In addition, long lifetimes are also desirable in the nuclear rocket development program to minimize the number of reactors required and the attendant long delays between tests if the reactors must be changed after each firing.

Perhaps the most important item on the list is that the nuclear rocket powerplant be developable. If it cannot be developed into a reliable man-rated system, it makes little difference what specific impulse can be attained, how many times the reactor can be recycled, or how long an operating life it may achieve. Besides recyclability and long life, the key to a system that can be developed is finding a concept that can be exhaustively tested in ground test facilities. Important in a test program is the ability to test reactor components and subsystems by themselves to a high degree of perfection before as-

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sembly into a complete powerplant. That is not to say that complete powerplant tests are not necessary. Not at all; complete powerplant tests are necessary to find the problems due to interactions of components. All difficulties that are found by component testing save much more costly and time-consuming full engine tests. Therefore, a reactor that has a high degree of component separability is highly to be desired.

## TUNGSTEN-WATER-MODERATED CONCEPT

After studies involving many reactor concepts, including fast and thermal, a thermal system using water as the moderator and tungsten enriched in the 184 isotope as the fuel element material appeared to be the most attractive.

The basic concept that evolved is very similar to the HTRE No. 1 reactor from the days of the Aircraft Nuclear Propulsion Program. A schematic of this reactor is shown in figure 1. It is composed essentially of an aluminum tank of water, which contains aluminum tubes joining aluminum headers at the top and bottom of the tank. Water fills the space surrounding the tubes. Fuel elements composed of concentric cylindrical plates of nichrome containing fully enriched uranium dioxide are held within the aluminum tubes. Air passes through these fuel elements, is heated, and is discharged from the bottom of the core. A fibre-type silica insulation about 1/10 inch thick contained within thin stainless steel cylinders running the full length of the core reduces the heat loss from the hot gases and fuel elements to a negligible fraction of the reactor power. The heat transferred to and generated in the water by neutron and gamma heating is removed by passing the water through an air-cooled radiator. This reactor can be converted to a nuclear rocket by utilizing hydrogen as the coolant, instead of air, and replacing the nichrome with tungsten fuel elements. A water-to-hydrogen heat exchanger replaces the air-cooled radiator. There is more than enough cooling capacity in the hydrogen propellant to cool the water moderator.

Figure 2 shows a photograph of a full-scale model of a tungsten-water-moderated nuclear rocket. An aluminum pressure vessel is completely filled with water except for the aluminum tubes, which contain the tungsten fuel elements and flowing hydrogen. The water-to-hydrogen heat exchanger is divided into six equally spaced segments, one of which is shown at the top. The hydrogen from the nozzle, which would be located to the right, enters the tubes of this heat exchanger, which removes the heat generated in the water. The hydrogen then enters the reactor-inlet plenum. From this region the hot hydrogen is expanded through the nozzle to produce thrust at specific impulses of 800 to 900 seconds. The water moderator is circulated through the core and heat exchanger by means of a water pump and inlet and outlet water plenums.

Figure 3 shows a sectioned view of a typical fuel element. The fuel element material in the form of five concentric cylinders of clad tungsten - uranium dioxide material is shown sectioned in this photograph. The fuel cylinders are supported and spaced by fuel support pins. The front support pins to the left pass through and are fastened to a tungsten fuel support tube. The fuel support tube runs the entire length of the reactor and provides a gap between it and the



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water-cooled aluminum tube, which is filled with stagnant hydrogen. The stagnant hydrogen gap about 1/8 inch thick contains a thin molybdenum radiation shield. This technique of insulation reduces the heat loss from the fuel cylinders and hot hydrogen to a fraction of 1 percent of the full reactor power. Considering the fact that 6 to 7 percent of the reactor power is generated within the water anyway by neutron and gamma heating, this small additional heat load is hardly of any consequence. The fuel cylinder stages are only about $1\frac{1}{2}$ to 2 inches long to minimize thermal expansion problems. About 20 to 30 stages are required for a full reactor length.

It is apparent that the high-temperature problems of this reactor concept are concentrated within individual isolated small fuel elements. The remainder of the reactor is made entirely of aluminum, which is water cooled at all points. The core structure being fabricated of a ductile metal and operating at essentially a constant temperature should present a minimum of problems in development. In fact, the entire water side of the reactor, which represents the major structural components, can be developed to a high degree of perfection without resorting to nuclear testing until all the major problems have been eliminated.

The individual fuel element can also be developed to a high degree of perfection relatively rapidly because of its small size. This can be done by means of out-of-pile electrically heated tests, hot hydrogen flow tests, furnace tests, vibration tests, and other similar tests. In-pile flow tests can also be carried out to more nearly simulate the complete nuclear rocket environment. Because of the relative ease and low cost of developing single fuel elements, several alternate designs could be developed simultaneously and the best one chosen for the final hot reactor development, but only after the major bugs have been worked out in the fuel element development program. Advanced fuel element concepts, perhaps for higher temperature or higher power density, can continue to be developed while the first nuclear powerplant is undergoing final development. These advanced fuel elements can eventually be used to replace the existing elements without major core modifications to uprate the performance. A reactor concept with such flexibility in development should provide the least risk in achieving a useful man-rated nuclear rocket with a minimum of time and cost.

## MATERIALS RESEARCH

The most important problem area of any nuclear rocket concept is providing fueled materials capable of retaining fissionable material at temperatures in the range of $4500^{\circ}$ to $5000^{\circ}$ F while heating hydrogen at extremely high flow rates and heat fluxes. Accordingly, the effort on materials at Lewis has received the greatest attention. The first endeavor, when the advanced nuclear rocket program was started in late 1955, was to find high-temperature fuel element materials that had the potential of the highest temperature, recyclability, and long life. The first step involved screening more than 30 high-temperature ceramic and metallic materials for compatibility with uranium dioxide (the most refractory uranium compound). Fortunately, it was found that the most refractory metal was compatible with uranium dioxide and hydrogen, which was to be the propellant. It was thought that metals would have the most promise for recycla-

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bility and long life because of their great ductility and high strength when compared to ceramic materials. After selecting the tungsten - uranium dioxide combination for the primary materials research program, ways for manufacturing useful shapes were explored. A powder metallurgy dispersion of uranium dioxide in a tungsten matrix offered the greatest promise. Figure 4 shows how this material is made at present. Uranium dioxide powder is mixed with tungsten powder and cold pressed and sintered into a compact of about 90-percent theoretical density. This compact is then sandwiched between foils of pure tungsten about 1 or 2 mils thick. This "sandwich" is then rolled in a hydrogen atmosphere at temperatures approaching 4000° F. The rolling process increases the density to greater than 99 percent of theoretical and also bonds the clad metallurgically to the meat. The bond area cannot be distinguished in photomicrographs of the joint. It was found that high density and clad were required to prevent disastrous uranium dioxide vaporization above 4000° F.

Samples of elements such as these have been tested by electrically heating to temperatures above 5000° F in vacuum and in flowing hydrogen for varying amounts of time ranging from minutes to hours for large numbers of rapid thermal cycles with no adverse effects. In-pile tests were conducted about 3 years ago in the Westinghouse Test Reactor before it was shut down. Samples about 1 inch square, 30 mils thick, with 20 volume percent of fully enriched uranium dioxide in the meat, with only the flat faces clad with about 2 mils of pure tungsten, were tested in evacuated capsules such as shown in the exploded view of figure 5. Cooling was provided by thermal radiation through the molybdenum radiation shield to the water-cooled stainless walls of the capsule. Each of seven specimens was run for 4 hours at temperatures varying from 4720° to 5430° F. All of the specimens including the one operated at 5430° R for 4 hours indicated no loss of uranium dioxide through the clad faces. Figure 6 shows photomicrographs made of this specimen. The right-hand portion shows a region along the flat surface with the 2-mil clad. The uranium dioxide, which shows up as gray spots in this figure, shows no migration at all through the clad. On the other hand, a section through the unclad edge shows uranium oxide loss to a distance of 7 or 8 mils from the unclad edge. Besides indicating no effect of radiation on the readily observable properties of the fueled material, the in-pile tests conclusively show the need for the clad and that cladding is effective in reducing uranium dioxide loss to nothing at temperatures of at least 5430° R for 4 hours of operating time.

There is still much work to be done in utilizing this basic fueled material in suitable heat-transfer and flow configurations required for use in a nuclear reactor. The Lewis program is heavily concentrated in this area at present.

By means of hot hydrogen flow tests of tungsten fuel element designs, electrically heated fuel element simulation, thermal cycling tests, and vibration tests, Lewis is attempting to determine the operating limits and potential of fuel element geometries. Particularly important is the ability of the fuel element to withstand the large aerodynamic forces imposed by the very high hydrogen flow rates required for high power density.

There are other potential problem areas such as heat-exchanger operation without freezing of water, maintenance of the stagnant hydrogen insulation layer,



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insulation of the hot end reactor header plate from the hot hydrogen in the reactor exit plenum, and provision of a simple, reliable control system. Each of the anticipated problem areas has been considered to some extent. In some cases experimental work is being done or has been done to determine whether the anticipated problems exist, and, if they do, how serious they might be. From the work that has been done on these problems to date, Lewis is confident that they can be overcome.

## ANTICIPATED PERFORMANCE AND CONCLUDING REMARKS

Based on electrically heated and in-pile experimental materials and fuel element research, the use of tungsten - uranium dioxide fuel elements should permit operation with peak fuel element temperatures up to 5000° F for at least 4 hours of operation with no loss in fuel. The tungsten-water-moderated reactor utilizing these elements should produce hydrogen outlet temperatures of 4000° F and perhaps 4500° F with further development. The corresponding specific impulse would be 825 and 880 seconds, respectively, for hydrogen temperatures of 4000° and 4500° F.

Based on simulated fuel element test results the reactor should be completely recyclable and have an operating life measured in hours. Early design studies indicate thrust-to-weight ratios of greater than 10, perhaps approaching 25, at power levels of 1000 megawatts up to 10,000 megawatts and higher.

Even though the anticipated performance is based on some experimental experience, especially with regard to operating temperature, cyclability, and life, the actual thrust-to-weight ratios of a reliable man-rated system can only be determined when the actual powerplant is finally developed and all the compromises and problems of a complete powerplant are finally made and solved. Based on the studies carried along for the past 7 years, Lewis feels confident that the water-moderated-tungsten concept can be developed into a reliable man-rated nuclear rocket propulsion system useful for manned planetary flight.

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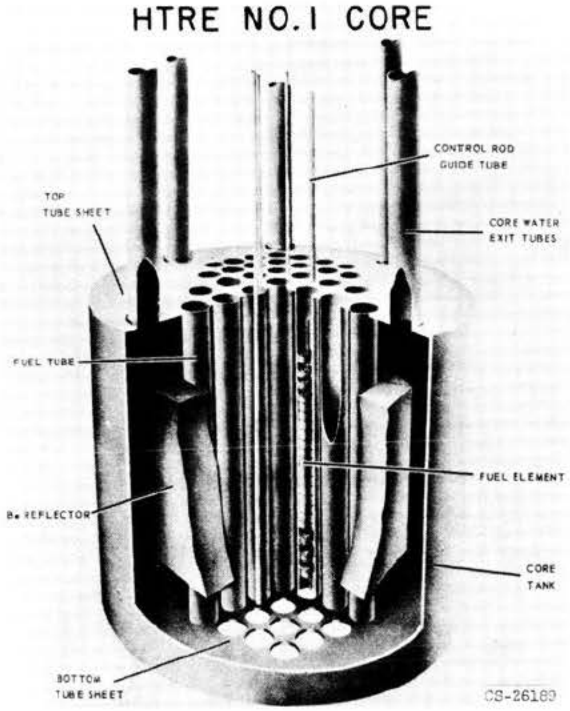


Figure 1

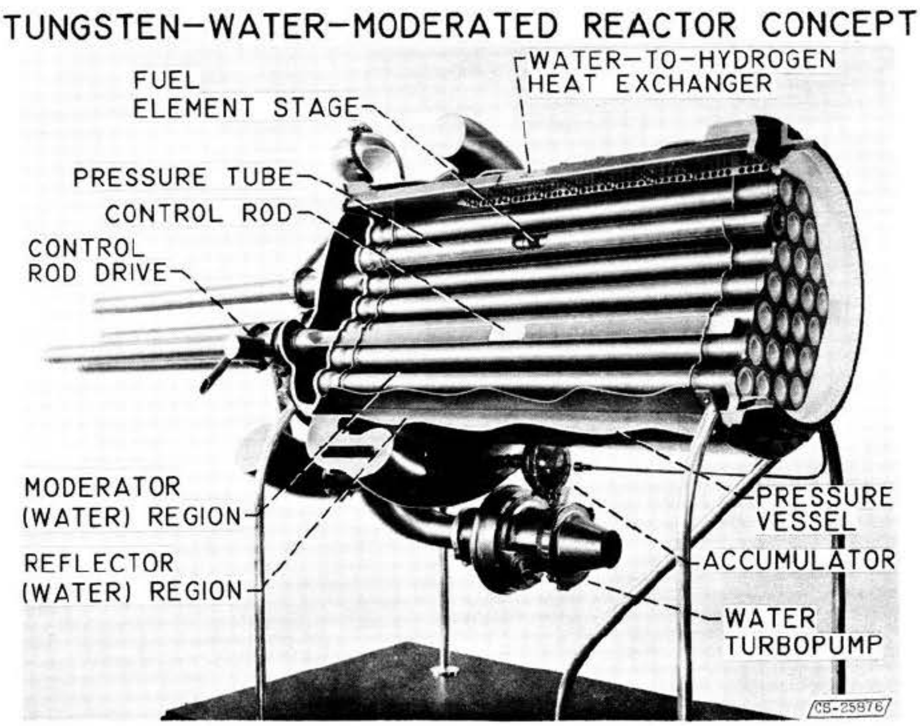


Figure 2



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TYPICAL FUEL ELEMENT ASSEMBLY FOR
TUNGSTEN-WATER-MODERATED
REACTOR CONCEPT

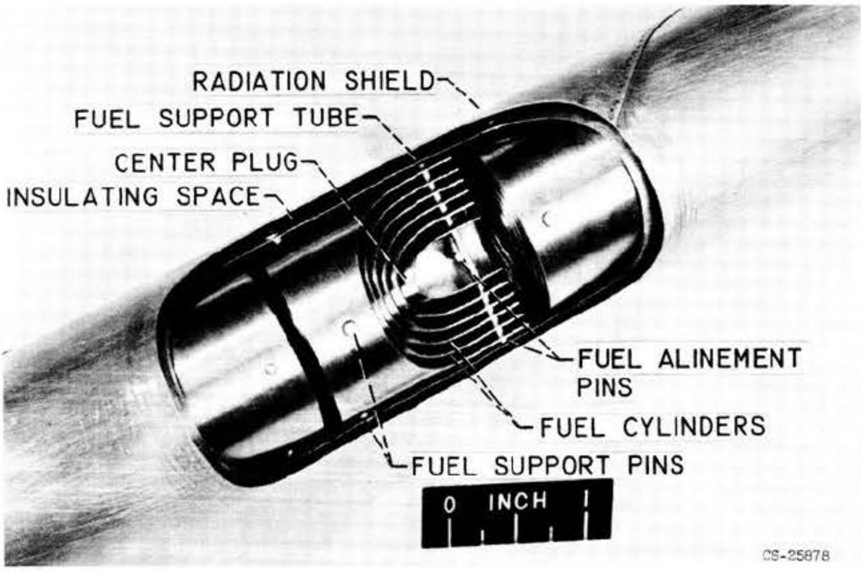


Figure 3

TUNGSTEN - URANIUM DIOXIDE FUEL ELEMENT

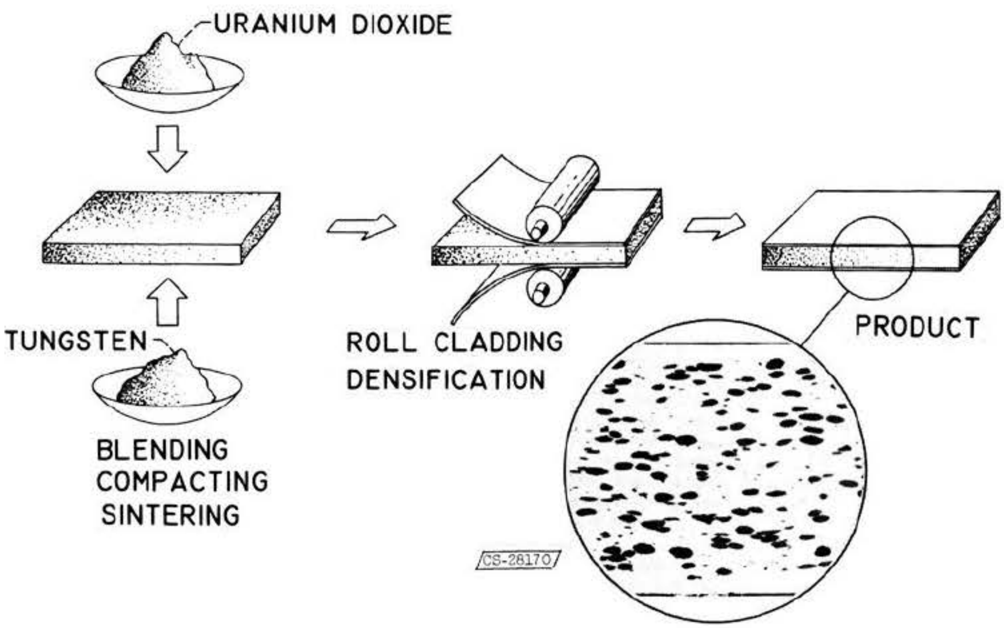


Figure 4

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# IN-PILE CAPSULE TESTS

| SPECIMEN | APPROX. CENTER REGION TEMP, °R | APPROX. SURFACE HEAT FLUX, BTU/SEC IN.$^2$ |
|---|---|---|
| 1 | 4900 | 0.74 |
| 2 | 4720 | .63 |
| 3 | 5050 | .84 |
| 4 | 5200 | .94 |
| 5 | 5430 | 1.12 |
| 6 | 5330 | 1.04 |
| 7 | 5250 | .98 |

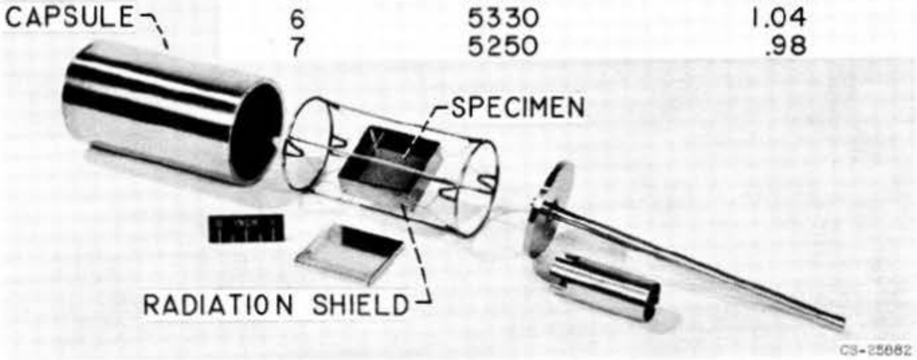


Figure 5

TUNGSTEN - URANIUM DIOXIDE FUEL ELEMENT SPECIMEN

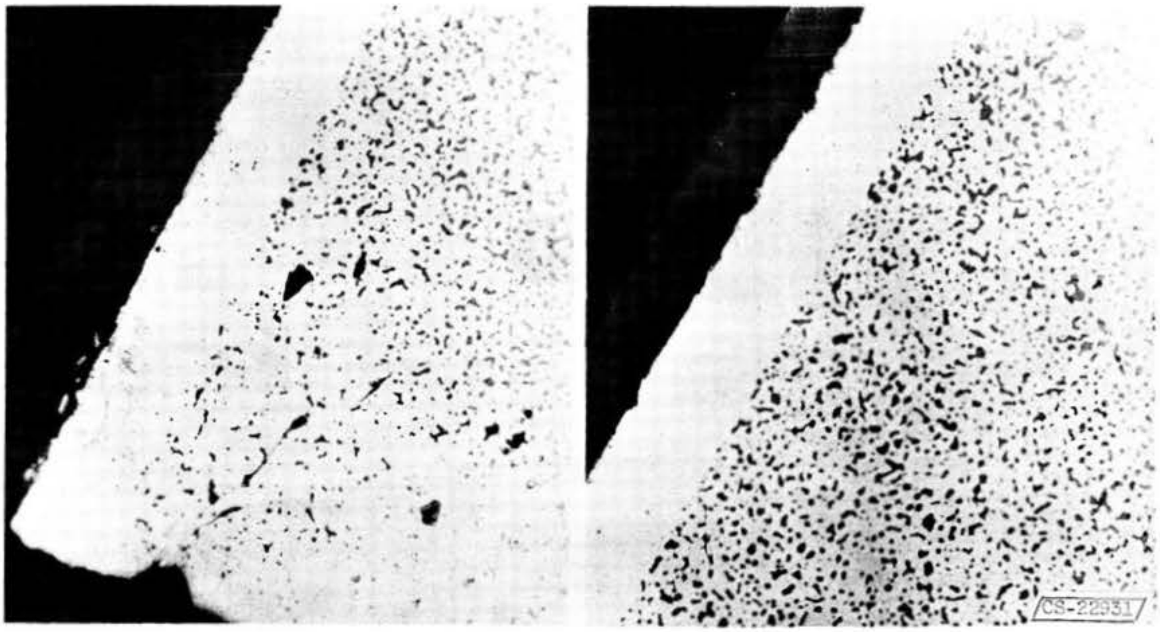


Figure 6



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